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Magnet Performance and RHIC Commissioning

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***Abstract* - The RHIC accelerator complex completed commissioning activities in 2000 and is presently operating for the first physics run. The complete ensemble of magnets was thus operating over an extended period for the first time. We review the magnet performance as well as relate machine performance characteristics and accelerator physics results to the various magnetic measurements made during the construction phase. The conclusions may be useful for the LHC Project.**

***Index Terms* — Superconducting accelerators, superconducting magnet performance, machine commissioning**

I. INTRODUCTION

The RHIC rings are shown in figure 1. The Collider is located in a ~3.8 km tunnel north of the AGS injector complex. The machine is comprised of two identical, quasi-circular rings separated horizontally by 90 cm, and oriented to intersect with one another at six locations. Having 3-fold symmetry each ring consists of three inner and three outer arcs and six insertion regions joining the inner and outer arcs. Each arc is made of 11 FODO cells with each half-cell consisting of a single dipole together with a spool piece assembly containing a quadrupole, sextupole and various concentric correction elements.

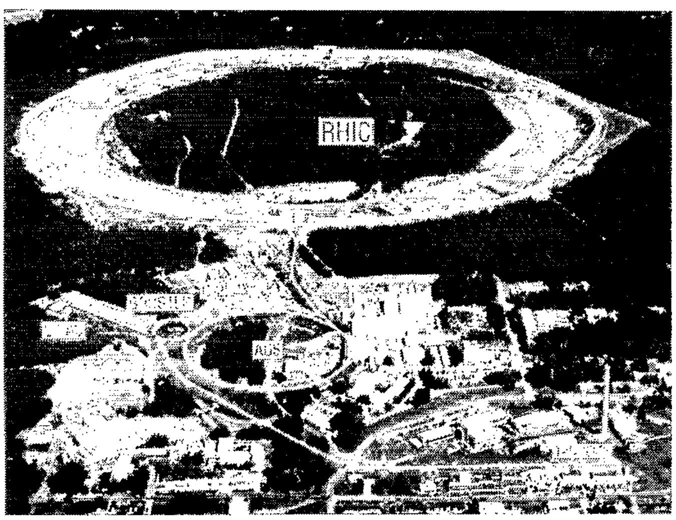


Fig 1: The RHIC Complex

The nominal design magnetic rigidity of the dipoles is 840 T·m which corresponds to a design field of 3.5 T at 100 GeV/u beam energy (250 Gev proton equivalent). Injection is at 100 T·m. The half-cells are 15m long and have beta-functions in the range 10.5 -> 50 m with a dispersion maximum of 1.8 m. These relatively small values are dictated by the need to minimize the physical size of a beam (i.e. maximize dynamic aperture and thus intensity lifetime) with relatively large normalized emittances (40π mm-mrad 95%, 1.2 eV-s/u). The dipole coil i.d. of 8 cm is determined by the beam size at injection and also the projected emittance growth which occurs during a store at the lowest collision energy of 30 GeV/u. The quadrupoles run at a maximum gradient of 72 T/m and also have a coil i.d. of 8 cm.

There are a total of 360 8cm dipoles and 420 'spool piece assemblies' of 8cm quadrupoles, correctors and sextupoles (CQS). The dipoles, quadrupole and sextupoles were built in industry with the CQS element integration performed at Brookhaven. There are 144 large aperture IR magnets of various types, all of which were fabricated at Brookhaven.

The RHIC complex was first operated for engineering run in 1999, commissioning runs followed in 2000 where the first beam collisions were observed. The first physics run is currently underway and at the time of writing this paper RHIC has achieved ~35% of the design luminosity using gold ions.

II. MAGNET TESTING AND ACCEPTANCE

At a relatively early stage in the Project it was recognized that with the available cryogenic facility at BNL it would not be possible to cold test every magnet. Instead of greatly expanding the test facility a decision was made to only cold test a limited number of the magnets.

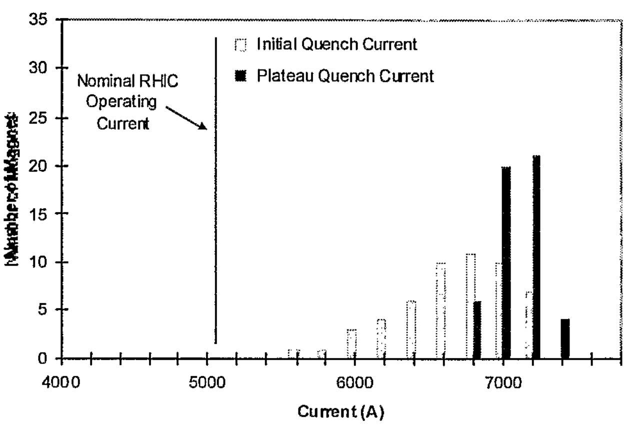


Fig.2 Dipole quench performance

With both the dipoles and the quadrupoles the first 10% of the magnets were fully tested (phase 1 production) and then when the production rate was increased then only 1-in-10 were cold tested. This decision was made easier by two main facts; the large quench margin of the arc magnets, and the excellent agreement between the field quality measurements for warm and cold measurements. The initial and final quench levels are shown in fig 2. for 50 production dipoles. None of the initial quenches of the dipoles is within 500A of the 5KA operating current. The quadrupoles have even more margin. The large operating margin is due primarily to the improvement in Nb-Ti superconductor performance during the initial phases of the project.

Figure 3 shows the warm-to-cold correlation of the sextupole harmonic of the dipoles. In addition to the small random spread, there is a systematic offset arising from the superconductor magnetization. Using this information it was possible to determine the field harmonics to within a few tenths of a unit from warm measurements. Similar correlations for the other field harmonics proved sufficient to satisfy the accelerator physics requirements for accuracy.

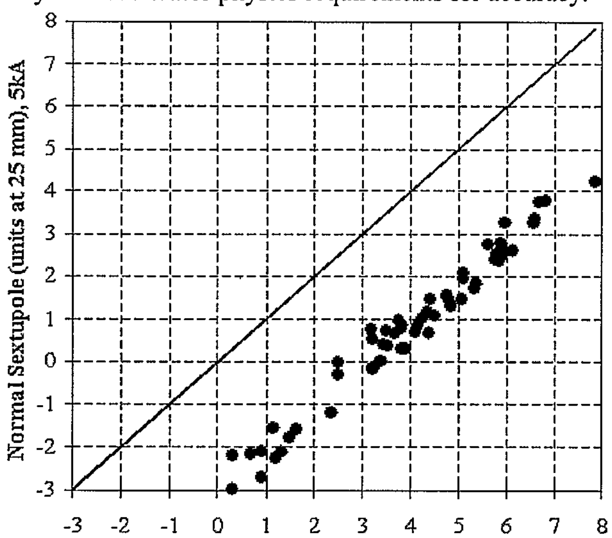


Fig 3. Warm-to-cold Field correlation

The interaction region elements did not have the same quench margin as the arc magnets and each one of these was cold tested. The performance of the magnets in the ring has fully endorsed this limited testing protocol with all magnets reaching the operating current with no training quenches in the arc magnets. The beam separating dipoles on either side of the IP were anticipated to need training and this indeed proved to be the case. Each ring required about 10 training quenches to reach design energy.

Given the cost of magnets, magnet acceptance for the ring is a subtle process which directly balances accelerator performance with cost considerations. The field quality of the RHIC magnets was generally considered to be 'very good' and no magnets were rejected on this, or indeed any, criterion. In order to avoid magnet rejection then several mechanisms were employed: some dipole sorting was employed on transfer function together with some primitive field quality sorting. A complex field quality assessment was employed to determine the best quadrupoles for the high luminosity IP's. Some sorting of sextupoles was also employed based on quench current where the requirements between focusing and defocusing locations varies greatly. The fact the no magnet was rejected was not only a success for the accelerator physics group but also the detailed analysis employed by the magnet builders during the production process. Potentially troublesome production trends were detected and corrected before reaching a level which impacted acceptance.

III. Specialty Magnets

In addition to the standard superconducting elements two aspects of the machine design required special elements: transition crossing and polarized beam operation. RHIC, in common with other superconducting accelerators, has a relatively slow ramp rate (25A/s). Due to the low injection energy of 10 Gev/u it proved difficult to implement a lattice design which avoided crossing transition energy. Transition is the beam energy where the additional path length experienced by higher energy particles is balanced by the increased velocity resulting in a constant revolution frequency. Under these conditions there is a loss of longitudinal phase focusing and the beam becomes unstable. In order to avoid this situation RHIC was designed with fast pulsed superconducting quadrupoles which are capable of producing a rapid change to the RHIC lattice and hence the transition energy to allow the beam to 'jump' the instability. Rapid ramping superconducting magnets are somewhat of a novelty, although GSI is considering a rapid cycling synchrotron as a future facility. Figure 4 shows the applied voltage and resultant current in these magnets.

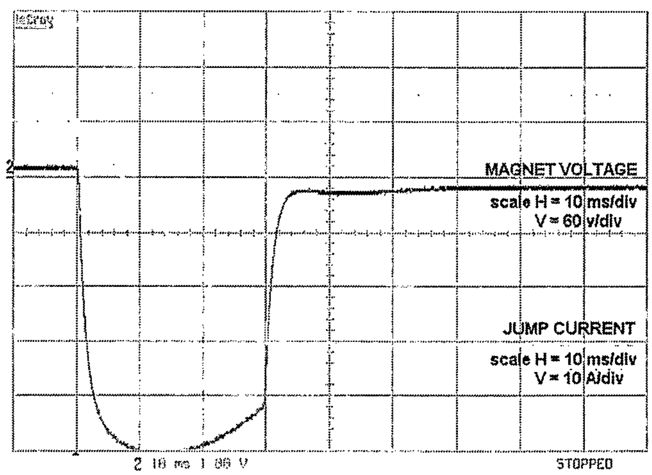


Fig 4. Current (40A) & Voltage (250V) V's time (10ms/div)

Using trim quadrupole windings fabricated with a single wire it has proved possible to achieve dI/dt values in excess of 4 kA/s without quenching the magnets. The jump has proved very effective in practice.

Polarized beams become increasingly difficult to maintain with increasing energy due to the increased density and strength of the spin resonances. Avoiding these effects by the use of tune jumps and harmonic orbit corrections becomes correspondingly less effective with increased energy. RHIC is by far the highest energy polarized beam facility envisaged and a different approach was necessary. The use of Siberian Snakes to preserve beam polarization has been postulated for a long time and has been implemented at RHIC. A Snake providing a full 180^0 spin flip was designed and fabricated as part of this program. Each Snake is constructed from four 2m helical dipole modules. Figure 5 shows the design principal behind these magnets.

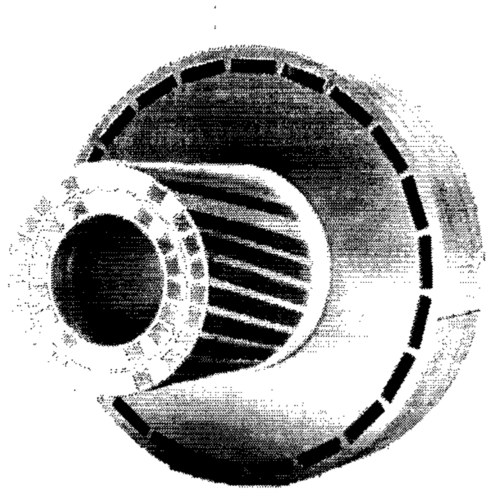


Fig.5. Helical dipole cold mass

Each 10cm aperture 2m dipole provides a complete 360^0 rotation of a 4T field. The magnet has two independent coil packages, shrunk fit together, with a 7-strand cable wound into slotted grooves machined into the requisite spiral shape. The coils are inserted into a spherically symmetric yoke. Two Snakes have been installed into each RHIC ring and have been operated with unpolarized beam. Initial polarized beam tests are scheduled for the current running period.

IV. Machine Optics

Measurements of optics in an accelerator can be considered to be analyzing the performance of the ensemble of magnets rather than single elements. In principle, an ensemble of magnets ought to be the sum of their parts but in practice, strings of magnets are subjected to different mechanical forces during cool-down and when cold than single elements. The powering scheme is generally different and magnets, especially those in and around the IR generally carry an assortment of electrical buss work.

One of the most basic beam measurements is a simple orbit measurement. An orbit difference where two orbits are subtracted removes many systematic errors from this measurement. Figure 6 shows one such measurement in the vertical plane in one half of the RHIC Blue Ring. The dots are the measured orbit offsets and the solid lines are the predictions. Other than some polarity reversed position monitors the agreement is very good.

A similar but more sensitive measurement is that of the machine lattice functions. The machine lattice is a (closed form) representation of the accelerator focusing properties.

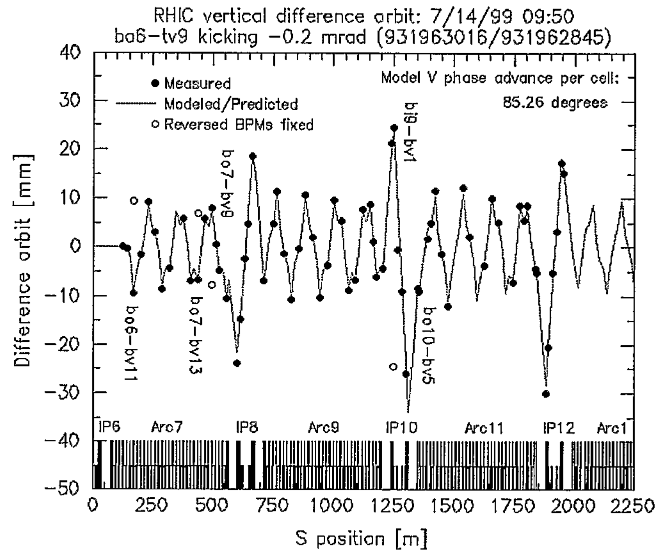


Fig.6. Measured and predicted difference orbit

Rather than simply subtracting two orbits from each other this measurement uses a kicked beam which is then tracked at each position monitor for the next 1000 turns. This turn-by-turn data is then Fourier analyzed to provide, among other things, the lattice beta-functions. This data is shown in figure 7.

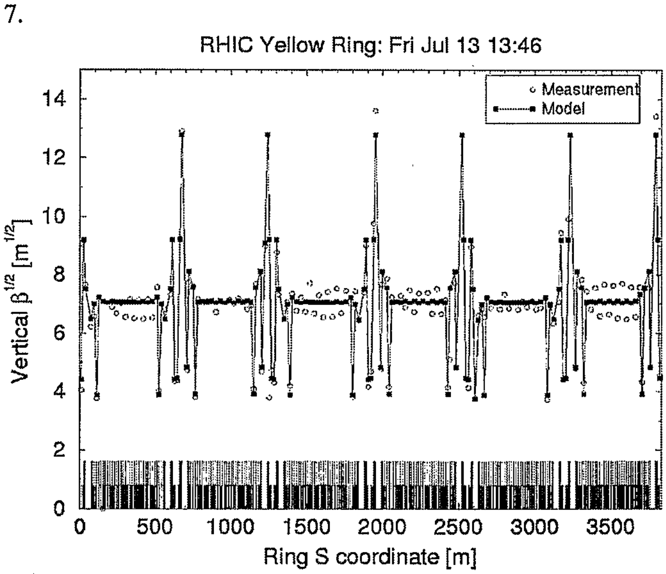


Fig.7. Measured and Predicted vertical beta functions

It is apparent that at the 10% level the model and the data agree, but one can observe optical mismatches between the interaction regions and the arcs. The arcs themselves look very good.

In addition to the design field components there are also skew field harmonics present in the magnets. The lowest order term (skew quadrupole) is present due to field errors in the magnets and can also be generated by roll misalignments in the quadrupoles. The effect of these skew terms is to introduce coupling into the machine. Coupling is the 'mixing' of the horizontal and vertical planes inside the machine. There are several ways to measure coupling. Figure 8 shows the results of creating a large horizontal offset locally across the IP's. The nominal skew fields are corrected to lowest order with the skew quadrupole correctors in the triplet quadrupole package. The rms. vertical orbit offset in the arcs is plotted versus the amplitude of the horizontal offset in the IP. If the calculated corrections are accurate then there will be no residual vertical offsets in the arcs independent of horizontal displacement. If the skew terms are not fully compensated the one would expect a vertical offset linearly proportion to the horizontal one.

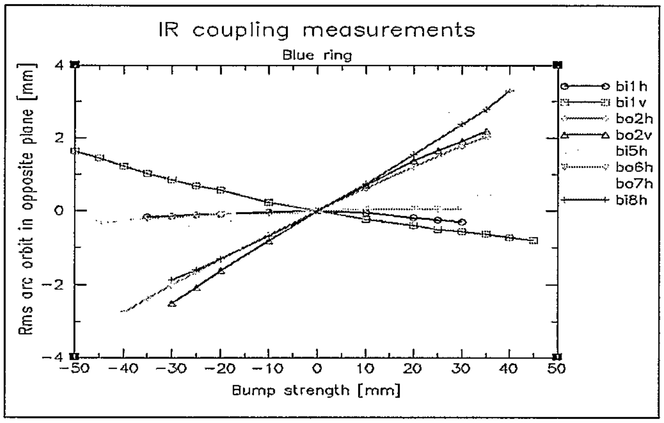


Fig.8 IP Coupling

The data from 8 IP's are shown in figure 8. While some of the IP's are well described by the estimated skew field (and hence well compensated) just as many are not. Residual orbits of several mm are visible in the arcs with mismatch showing no systematic effect. The vertical amplitudes are not too large so it is reasonable to conclude that the triplet skew fields are understood qualitatively but not quantitatively. An alternative method of empirically determining skew fields involves using the machine tune. Skew fields will also 'couple' horizontal and vertical tunes as well as orbits. The minimum achievable tune separation is thus a sensitive indicator of coupling. Figure 9 shows a tune scan of horizontal and vertical tunes in one of the RHIC rings. In this data set the IP's were fully compensated locally so that only the coupling in the arc sections remained in the ring. The measured versus predicted data agree well.

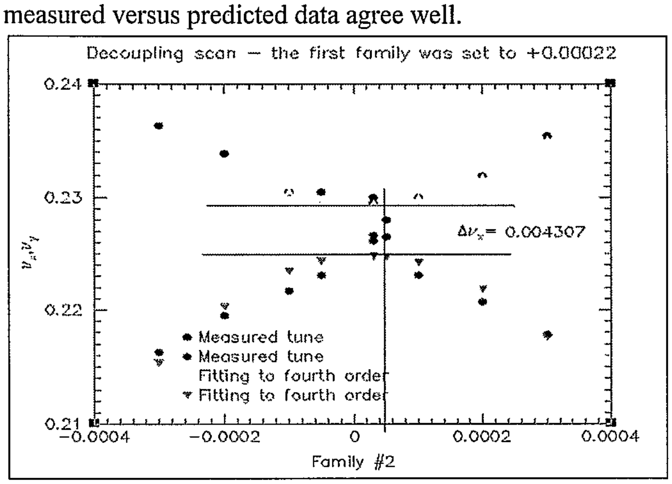


Fig 9. Minimum tune separation

The lowest order machine optics measurements would indicate that the magnetic fields in the simple, repetitive arc sections agree very well with simulations. The more optically and mechanically complex IR sections are reasonably described but less accurately than the arcs. The (unproven) suspicion is that motion of the cold masses inside the triplet cryostats is the source of at least some of the effects seen. If the cryostats ever need to be opened up then a re-survey will be performed.

V. Dynamic Effects

Like all superconducting machine RHIC exhibits time varying fields at injection energies. The magnet cable has a high inter-strand resistance of 50-100 μ–Ω and a 6μ filament size so the persistent/eddy current effects are rather small but nonetheless discernable. Figure 10 shows the persistent current sextupole for 20 dipole magnets.

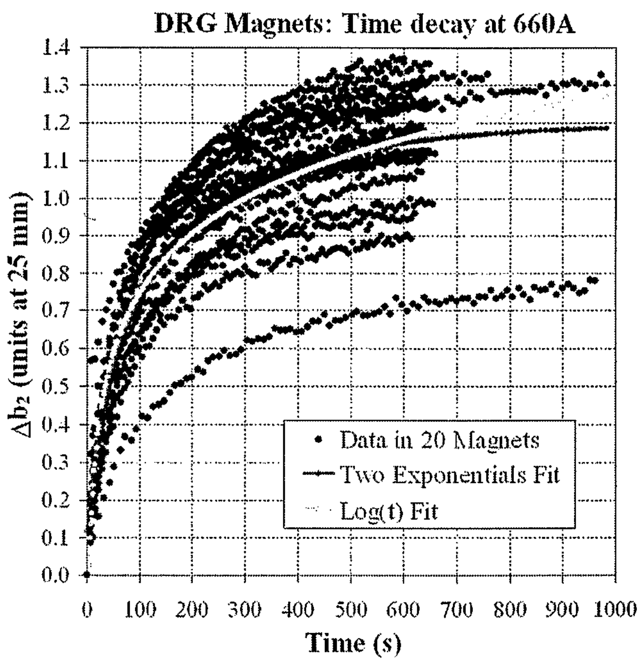
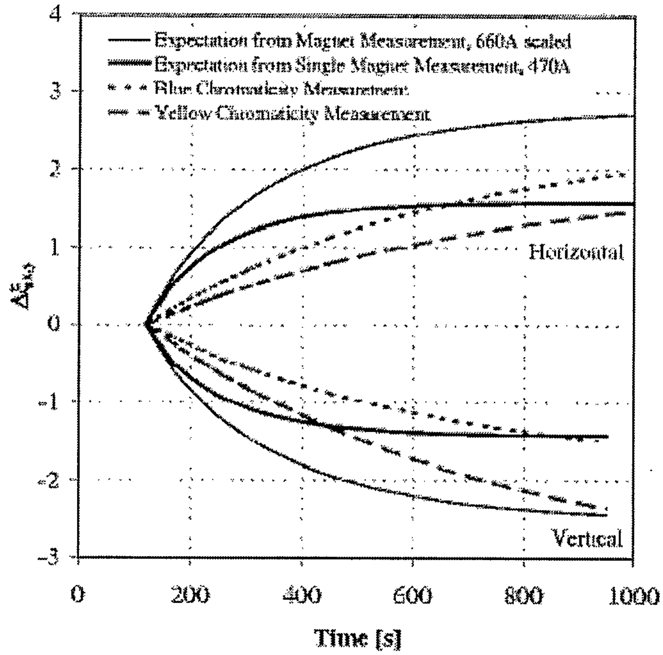


Fig.10 time dependence of the sextupole harmonic in the dipole magnets.

The change in sextupole is ~1 unit in 600s. The RHIC lattice is such that 1 unit of sextupole in the dipoles corresponds to only a few units of chromaticity. The machine chromaticity is totally due to the arc dipoles so it should be straightforward to predict the time dependant chromaticity at injection energy. The measured time dependent machine chromaticity as well as the predicted value is given in figure 11 for two different injection energies. Even though there is a relatively large random variation among individual dipoles the agreement is not good. The shapes of the curves do not track. This lack of agreement is not understood at this point.



Another dynamic effect encountered during acceleration is that of quadrupole tracking. There are 60 quadrupole circuits in each RHIC ring. The main ones are the Qf & Qd quadrupoles busses the other are the various elements at each IR used in the lo-beta squeeze. During acceleration, in order to keep the machine tune constant; each of these elements must maintain synchronism up the ramp. While this is fundamentally an issue for the power supply system not the magnets the differing complex impedances present by the various magnet systems, especially those involving shunt supplies, is a classic test of the electrical engineers skill. Figure 12 shows the output from the phase locked tune measuring system during a RHIC ramp.

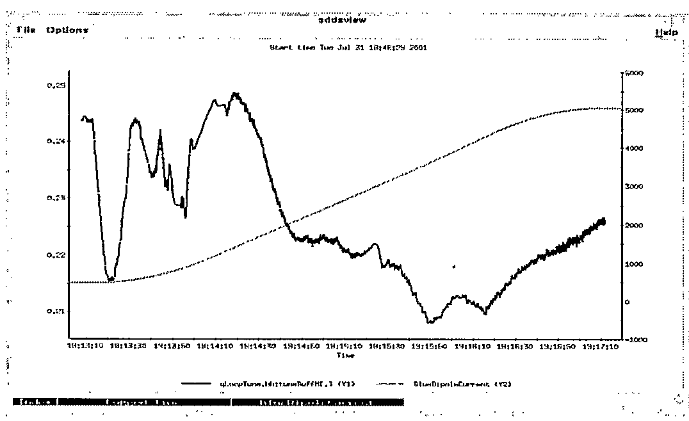


Fig 12. Tune variation up the ramp

The quadrupole synchronization is stable to $\pm$ 1 x 10^{-4} which is very good but not good enough. The desired factor of 5 improvement will only obtained by the use of feed back techniques.

VI. Operating Experience

After the three operating periods to date, the experience with the magnets has been very promising. After the initial shakedown period there has not been any failure of a major magnet. One of the pulsed correction quadrupoles has gone open circuit. This element has been removed from the system without any discernable impact. Several voltage taps (out of several thousand) have also failed. The critical voltage taps were wired in a redundant fashion with parallel circuits. In non-critical locations the adjacent circuits were used. During the first three operating periods the only failure which has required a warm-up is shown in figure 13.

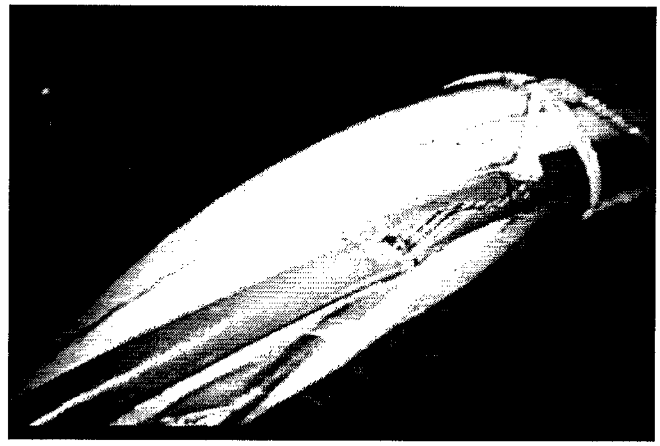


Fig. 13. A shorted internal wiring cable.

In the vicinity of the IR's then there is a significant amount of internal wiring for the independent lo-beta quadrupole circuits which passes through the magnets in wiring bundles. One such bundle was chafed during the thermal cycling of the machine against an internal edge in a dipole.

VII. Conclusion

Commissioning the RHIC accelerator complex has required the usual amount of effort (and talent) from a large number of people. The magnet production program was quite successful with no completed magnets rejected as unsuitable for the machine. In spite of a limited cold testing program all the magnets installed in the ring achieved (or exceeded) the design energy. The magnet system has performed well during operation and has caused a minimal amount of downtime due to failures. During the first three years of machine operation there has been no major magnet failures. The quench performance of the magnets has been as expected. The machine optics in the arcs has agreed very well with the predictions based on the magnetic measurements made during production. The interaction regions are not as well understood as the arc regions with disagreements with the calculations at the 10% level for the first order optics. It is suspected that the complex mechanical nature of the IR cryostats results in some motion of the cold masses during cryogenic cycling.

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